The Holocene 13,6 (2003) pp. 851–861

Dendroclimatic reconstruction of maximum summer temperatures from upper treeline sites in Interior British Columbia, Canada

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Received 1 May 2002; revised manuscript 9 September 2002

A HOLOCENE RESEARCH PAPER

Abstract: Two independent reconstructions of maximum May–August temperatures are developed from a new network of Engelmann spruce tree-ring chronologies at treeline sites across Interior British Columbia (IBC). The IBC reconstruction (AD 1600–1997) uses the longest three ring-width (RW) and two maximum latewood density (MXD) chronologies from the region. The shorter (regional) reconstruction (REG, 1845–1997) is based on an independent, more broadly based network of chronologies (12 RW and 5 MXD) and verifies the regional signal in the parsimoniously sampled IBC reconstruction. Both models explain 53% of the regional temperature variance (1912–1995) and correlate strongly (r = 0.92) over their common period. The IBC reconstruction indicates two prolonged cooler intervals, *c*. 1620–1710 and 1775–1880, separated by warmer conditions that approached late twentieth-century normals between *c*. 1710 and 1730. The mean anomaly over the 1600–1900 period is estimated at 0.38°C below the 1961–1990 mean with the seventeenth century (1601–1700) being marginally colder than the nineteenth century (–0.53: –0.49°C). Both reconstructions model the rise in temperatures from the 1880s to 1940s and indicate that maximum summer temperatures since 1930 have been warmer than at any period since 1600. The IBC record from 1600–1900 is very similar to the mean summer-temperature record reconstructed in the adjacent Canadian Rockies, providing mutual verification for the regional nature of the signal in both reconstructions. This is the first maximum summer-temperature reconstruction from North America. Significant changes are also noted in the relationships between summer mean, maximum and minimum temperatures in this region in the last few decades with a greater absolute rate of increase in mean and minimum temperatures. These changing relationships suggest it is prudent to model tree-ring response to a variety of temperature parameters rather than using mean-temperature values.

Key words: Dendroclimatology, tree-ring network, ring width, maximum density, summer maximum temperatures, British Columbia, Canada.

Introduction

Over the last two decades, several studies have demonstrated significant potential for the reconstruction of summer-season temperatures from Northern Hemisphere coniferous species at treeline sites (e.g., D'Arrigo and Jacoby, 1992; Briffa *et al*., 1992; Luckman *et al*., 1997). Maximum tree-ring density has proven particularly useful as a proxy for summer temperatures in large-scale chronology networks (Schweingruber and Briffa, 1996; Briffa *et al.,* 2001). However, there is a need for complementary investigations at intermediate scales between these large, sparsely sampled networks and individual long records from single sites that utilize both ring-width and maximum-density data. This paper presents results from a new network of Engelmann spruce treeline sites in British Columbia (BC) that extends regional chronology coverage, provides verification of earlier work in adjacent regions and represents the first reconstruction of summer maximum temperatures in North America. We also present information about the changing relationships between mean, maximum and minimum temperatures that may have important implications for dendroclimatological work.

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 10.1191/0959683603hl663rp

A new tree-ring network for the southern Canadian Cordillera

Dendrochronological studies at upper treeline in the southern Canadian Cordillera have focused on either Vancouver Island (Smith and Laroque, 1998; Laroque and Smith, 1999) or the Canadian Rocky Mountains (Parker and Henoch, 1971; Luckman *et al.*, 1985; 1997; St George and Luckman, 2001). Only two treeline spruce chronologies are available from the large intervening area (Schweingruber, 1988). Recent work in the southern Rockies has established networks of chronology sites using Engelmann spruce (*Picea engelmannii* Parry), whitebark pine (*Pinus albicaulis* Engelm) and alpine larch (*Larix lyallii* Parl) that typically average 300–400 years (Luckman, 1996) but include millennial-length chronologies from each species. Temperature reconstructions have been developed from some of these data using alpine larch (Colenutt, 2000) and Engelmann spruce (Luckman *et al.*, 1985; 1997; St George and Luckman, 2001).

In 1998 a network of 20 new Engelmann spruce chronologies was sampled from sites across southern British Columbia (Figure 1). All sites were at or within 100–200 m of upper treeline, including sites at Kokanee and Kootenay Pass close to the two chronologies sampled in 1983 (Schweingruber, 1988). An additional ring-width chronology was developed for Harts Pass in Washington State from five spruce chronologies sampled in 1992 (Peterson and Peterson, 1994). This 21-chronology network extends the distribution of Engelmann spruce treeline sites about 500 km westwards to the Coast Mountains, allowing comparative studies with results developed from chronologies of the same species elsewhere in the Canadian Cordillera.

Sample preparation, measurement and chronology development

Chronologies were developed for both ring-width and density parameters as previous work has demonstrated the utility of maximum-density series in climate-reconstruction studies in this region (Parker and Henoch, 1971; Luckman *et al.*, 1985; 1997). For ring-width data the samples were prepared using standard procedures (Stokes and Smiley, 1968). Visual cross-dating was verified after measurement using the computer program COFECHA (Grissino-Mayer *et al.*, 1997). Ring-width series were detrended using negative exponential or negative linear regression functions and averaged to form site standard chronologies. Density data were developed for the seven longest chronologies using facilities at the Tree-Ring Laboratory of Lamont Doherty Earth Observatory, New York, following methods outlined by Jacoby *et al.* (1988; see Wilson, 1999). Although earlywood width, latewood width, and minimum and maximum density were determined for each year, only ring-width (RW) and maximum-density (MXD) data were used in this study as they have consistently proved to be the best ring parameters for the reconstruction of past temperatures from Northern Hemisphere conifers (Briffa *et al.*, 1992; 1994; 1996; 2001; Briffa and Schweingruber, 1992; Jacoby *et al.*, 1988; Luckman *et al.*, 1997). The only age-related trend in most MXD series is a linear decrease with age. Therefore, MXD series were detrended using negative or zero slope linear regression functions.

Ring parameter characteristics and regional signal assessment

Comparison between ring-width and maximum-density data

Table 1 presents summary data for the 21 RW and 7 MXD chronologies (full details are given in Wilson, 1999). Mean ring-width values are higher (1.28: 0.71 mm) than those from spruce sites in the Canadian Rockies (St George and Luckman, 2001). This, in part, reflects differences in mean stand age between the two regions (188: 281 years) as the younger trees generally have higher growth rates. Mean sensitivity values are typical for spruce and comparable to those for the Canadian Rockies (0.18; St George and Luckman, 2001). In general, these RW series show low mean sensitivity, high autocorrelation and high between-tree variance (as measured by the standard deviation). MXD series show low between-tree variance, low mean sensitivity and low autocorrelation. The RW series have a stronger low-frequency component than MXD series and, because of the higher between-tree variability in ring-width series, more samples are necessary to develop robust mean RW chronologies. MXD series generally show a lower amplitude of long-term persistence but have strong year-to-year variability.

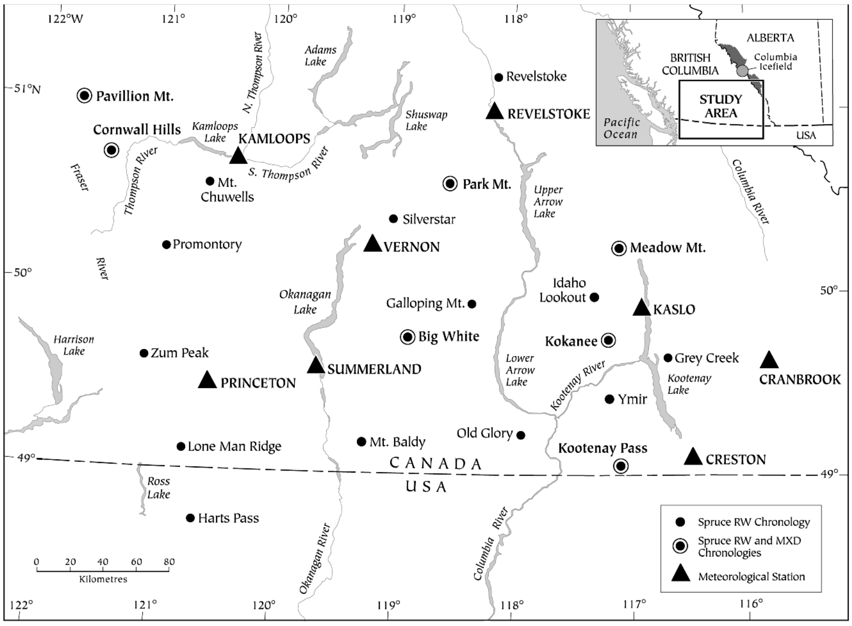

Figure 1 Tree-ring sites and meteorological stations in the Southern Interior of British Columbia.

Signal strength assessment

The mean series correlation statistics calculated between standard chronologies indicate a much stronger common signal within the MXD data compared with RW data (Table 1). The expressed population signal (EPS) was used to quantify the signal quality of the individual chronologies (Wigley *et al.*, 1984). EPS values were calculated for each chronology using a 30-year moving window. This 'moving window' EPS approach provides an absolute measure of signal quality through time (Briffa, 1995). The last year of acceptable signal strength was defined as the central year of the last 30-year window with EPS >0.85 (Wigley *et al.*, 1984). The average number of trees needed to obtain an EPS >0.85 is 10 for RW and 6 for MXD chronologies. These results and the higher mean correlation values demonstrate the stronger between-tree signal in the MXD chronologies (Table 1).

Regional signal assessment

The mean between-site correlation for the MXD data ($r = 0.84$; 1800–1997; $r = 0.81$; 1900–1991) is much greater than for the RW data ($r = 0.48$; 1900–1991) indicating a stronger regional signal in the MXD chronologies. Regional signal heterogeneity was assessed by separate principal component analyses (PCA) for both RW and MXD standard chronologies. A varimax rotation was used to aid in interpretation of the individual site loadings on each eigenvector (Richman, 1986).

PCA of 21 RW chronologies was restricted to the 1900–1991 common period to allow maximal spatial coverage. Five principal components were identified with an eigenvalue >1.0 (Table 2). The first component is the dominant regional signal and explains 54.8% of the variance in the ring-width data matrix. Nine chronologies load most heavily on this component and five chronologies load strongly on PC2. The few chronologies that load upon PC3 are located in the west of the region. These loadings are significantly correlated with longitude of the site ($r = 0.68$) and PC3 correlates significantly ($r = 0.43$) with the annualized (previous September to current August) Pacific Decadal Oscillation Index from 1901–1991 (Mantua *et al.*, 1997). These observations suggest an oceanic influence upon tree growth in the west of the region. PCs 4 and 5 appear to be site-specific, show no regional pattern and are difficult to interpret.

PCA of the MXD chronologies over the 1900–1991 period yielded one significant PC that explains 83.7% of the common variance (Table 2) and indicates that all seven MXD chronologies are responding similarly to a common forcing function across the region sampled. The first PCs from the RW and MXD PCA are naturally orthogonal ($r = -0.006$) over the 1900–1991 period suggesting the influence of different forcing mechanisms upon these parameters.

Table 1 Tree-ring chronologies used in this paper

Site name	Elev. (m)	Length (years)	RW EPS >0.85	MXD EPS >0.85	R
Glacier	2050	1798–1997	1955		N
Revelstoke	2000	1718–1997	1825		REG
Meadow Mt	2100	1669–1997	1780	1745	REG
Kokanee	1950	1710–1997	1820	1790	REG
Idaho Lookout	2000	1731–1997	1925		N
Ymir	1980	1573–1997	1845		REG
Old Glory	1900	1724–1997	1800		REG
Kootenay	1950	1698–1997	1745	1740	REG
Park Mt	1830	1477–1997	1635	1625	IBC
Silverstar	1700	1822–1997	1870		N
Galloping Mt	2050	1714–1997	1815		REG
Big White	2000	1512–1997	1710	1715	IBC
Mt Baldy	1875	1569–1997	1825		REG
Grey Creek	2000	1789–1997	1915		N
Pavilion Mt	1950	1694–1997	1755	1735	REG
Cornwall Hills	1980	1554–1997	1730	1720	REG
Mt Chuwells	1800	1708–1997	1780		REG
Promontory	1680	1816–1997	1960		N
Zum Peak	1680	1702–1997	1865		N
Lone Man	1850	1809–1997	1845		REG
Harts Pass	1950	1585–1991	1655		IBC

R = climate-reconstruction predictors, REG = regional, IBC = Interior British Columbia, N = not used.

	Raw Data		Standard Chronology			
	MSL (years)	Mean value	Std	Ms	1st AC	rmt
Ring width (21)	188	1.28	0.34	0.20	0.65	0.29
Maximum density (7)	238	0.81	0.13	0.12	0.32	0.44

MSL = mean sample length; Std = standard deviation; Ms = mean sensitivity; rmt = mean between series correlation; 1st AC = 1st order autocorrelation.

Development of a regional climate temperature series

No appropriate regional temperature series was available for the area shown in Figure 1. Therefore a regional series was developed from the eight longest station records from interior British Columbia distributed across the region (Figure 1). These records are from the Historical Canadian Climate Database (Vincent and Gullett, 1999) and have been corrected for data inhomogeneities and missing values. They share a common period from 1912 to 1995 (Vincent, 1998) and four records extend back to 1895. PCA of the seasonal and annual records of these eight stations identified only one significant PC in each case that accounted for between 82.9% (summer, JJA) and 96.1% (winter, JFM) of the variance. Although these stations were selected based primarily on their position and length of record, the strong common signal suggests that a regional record developed from these eight records can be considered representative for this region.

Monthly values for each station were standardized as z-scores and these station-based, monthly z-scores were averaged across the stations to calculate monthly z-scores for the regional average series. The monthly z-scores were converted to 'absolute' temperature values using the average of the means (grand mean) and standard deviations (grand standard deviation) of each of the original monthly series. This produces a regional average temperature series that has not been biased by differences in the variance of the original data sets (Jones and Hulme, 1996). The resultant monthly series were converted to anomalies (°C) from the 1961–1990 reference period. Regionalized temperature series were calculated for mean, maximum and minimum temperatures.

Table 2 Summary principal component analysis results for (a) 21 ring-width (common period 1900–1991) and (b) 7 maximum-density chronologies (1800–1997) from Interior British Columbia

Site	(a) RW					(b) MXD PC1
	PC1	PC2	PC3	PC4	PC5	
Eigenvalue	11.5	1.9	1.9	1.2	1.0	5.9
% Variance	54.8	9.3	8.9	5.9	4.8	83.7
Cumulative var.	54.8	64.1	73.0	78.9	83.7	83.7

Climate-growth relationships

Correlation analysis of the relationships between tree-ring and monthly climate data was undertaken using a 17-month period from May of the previous year to September of the growth year. Figure 2 summarizes the results of the correlations between the dominant RW and MXD PCs and monthly values of maximum, mean and minimum temperatures over the 1912–1991 period common to all records. No consistent results were found in correlations between the PC scores and precipitation data from individual stations.

The strongest correlations are found between MXD data and temperatures for all months between March and August of the current growing season except July. In general, correlations are stronger with both maximum and mean temperatures, and the strongest correlation is with maximum August temperatures ($r = 0.71$). The correlations with mean temperatures are comparable to similar results from the Canadian Rockies (Parker and Henoch, 1971; Luckman *et al.*, 1997). Significant negative correlations with previous August temperatures are also observed.

The dominant RW component correlates positively with maximum and mean temperatures of June, July and September of the growth year and the previous December. Negative correlations are also observed with previous August temperatures. No significant correlations are observed with minimum temperatures. These results are generally similar to those obtained from the analysis of ring-width/mean temperature relationships for Engelmann spruce in the Canadian Rockies (St George and Luckman, 2001).

The dominant MXD and RW principal components both correlate most strongly with maximum and mean temperatures. As these components explain most of the variance in the tree-ring data (Table 2), reconstructions could be developed for either maximum or mean temperatures.

Dendroclimatic modelling: reconstruction of summer temperatures

The proxy climate record developed from tree-ring series contains a mixture of local and regional scale signals. Regional climate reconstructions inevitably compromise between developing long reconstructions based on a few sites and developing spatially representative records that integrate the common signal but are limited by the length of the shortest chronology in the network.

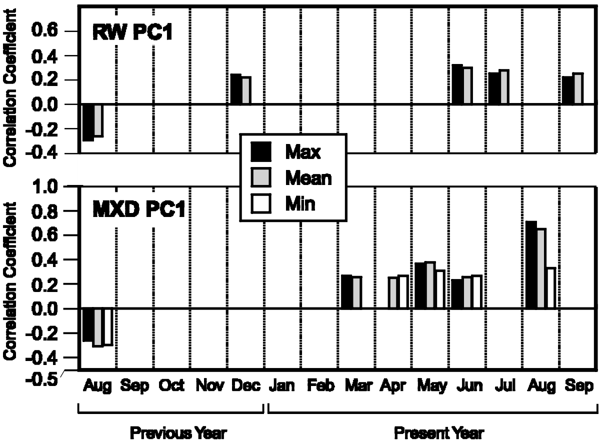

Figure 2 Significant correlations between monthly temperatures and the first principal component of the 21 RW and 7 MXD chronologies for the 1912–1991 period. Analyses were carried out for maximum, mean and minimum temperature records of all months from the previous May to the current September. Only correlations that exceed the 95% confidence limit are shown.

Two totally independent reconstructions are presented in this paper. The regional reconstruction (REG) is based on 12 RW and 5 MXD chronologies that maximize spatial representation but are of restricted length (1845–1997). The Interior British Columbia reconstruction (IBC) utilizes the three longest RW and two MXD chronologies withheld from the REG analysis to develop an independent reconstruction almost 400 years long (1600–1997). Comparison of the two reconstructions over the common interval (1845–1997) allows mutual verification of the common signal in these records and evaluation of the regional signal in the longer series. The chronologies used in each reconstruction are identified in Table 1. Five short chronologies were excluded from these analyses.

The regional reconstruction (REG; 1845–1997)

PCA (using a varimax rotation) was used to transform the 12 RW and 5 MXD chronologies into orthogonal predictors for multiple regression analysis. Four components were identified with an eigenvalue greater than 1.0 (Figure 3) and are comparable to those identified in the PCA for the full network shown in Table 2. PC1 portrays the unique variance of the MXD data, whereas PCs 2–4 correspond with PCs 1–3 of the previous RW analysis. The loadings of the RW chronologies on PC4 show a significant east–west relationship and therefore this component was not entered as a possible predictor for the REG reconstruction.

As previous year's climate can often affect current year's growth, it is common practice to lag the predictor series forward or backward by one or more years (Fritts, 1976). Meko (1981) notes that the sole reason for negatively lagged predictors entering into a regression equation is multicollinearity. Therefore, only the PCs of year t and $t + 1$ were included as potential predictors for the reconstructions developed in this paper. Six series were there-

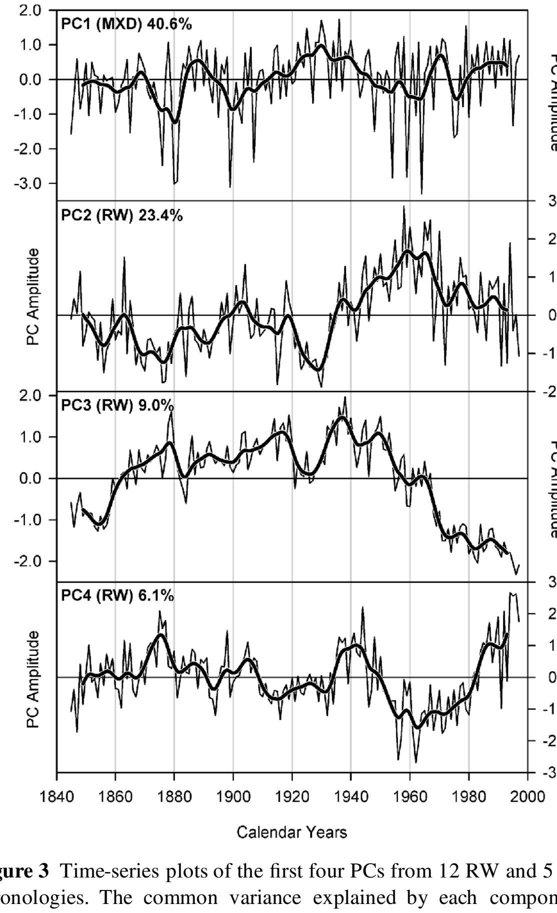

Figure 3 Time-series plots of the first four PCs from 12 RW and 5 MXD chronologies. The common variance explained by each component is shown in the top left-hand corner of each plot. The heavy line is a 10-year smoothing spline. PCs 1–3 were used for the REG reconstruction. PC1 and PC2 are comparable to the MXD and RW PCs used in Figure 2.

fore entered as candidate predictors into the stepwise multiple regression for the REG reconstruction ($PC1_t$, $PC1_{t+1}$, $PC2_t$, $PC2_{t+1}$, $PC3_t$ and $PC3_{t+1}$).

The Interior British Columbia reconstruction (IBC; 1600–1997)

Three RW and two MXD chronologies used in this reconstruction load strongly on the first PC for both RW and MXD in the full network PCA (Table 2). As their common variance therefore portrays the dominant signals in the region, the chronologies were averaged to produce separate mean RW and MXD predictor chronologies. Averaging allows the reconstruction to be extended forward to 1997 (Harts Pass ends in 1991) although calibration is restricted to the 1912–1991 interval. The correlation between the mean RW and MXD series over the period 1600–1997 is 0.098 and does not pose a collinear problem in the regression model. The decrease in the common signal over time was assessed by calculating the 'pooled signal' between the chronologies using a 30-year moving EPS window (Briffa, 1995). The between-site common variance decreases through time in both predictor series and negative correlations indicate a lack of common growth forcing in the sixteenth century. The reconstruction was terminated at 1600 and should be interpreted cautiously during the early seventeenth century as the EPS statistics of both predictor series are relatively weak. Four predictor variables were entered into the regression model for the long reconstruction (MXD_t, MXD_{t+1}, RW_t and RW_{t+1}).

Calibration trials and reconstruction verification

Calibration trials were undertaken for both reconstructions using seasonal combinations of temperatures based on the exploratory analyses shown in Figure 2. May–August maximum temperature was the optimal common parameter explaining 53% of the variance in the instrumental climate record for both reconstructions. Reconstructions were also developed for mean May–August temperatures (REG_m and IBC_m, respectively).

For calibration, the full calibration period was split into early and late intervals and separate calibration and verification trials undertaken on both periods. Calibration of the early, late and full models was also verified using independent climate data from the period 1895–1911. All models for the REG and IBC reconstructions performed very well in calibration and verification against May–August maximum temperatures (Table 3). The REG_m reconstruction performs similarly well but significant autocorrelation is identified in the full model residuals. The IBC_m reconstruction performs less well (42%), fails many of the more robust verification statistics in the 1895–1911 period (Table 3) and has a strong linear trend in the full model residuals. This verification failure in the early period is due to the increasing mean temperatures of the last few decades that shift the resultant predicted values upward. This results in overprediction of values in the 1895–1911 period. The reasonable performance of the REG_m reconstruction reflects the utilization of $PC3_{t+1}$ as a predictor (there is no comparable component in the IBC_m reconstruction). PC3 differs in long-term trend from PC2 (Figure 3) and probably reflects a more complex response to regional climate. Although the inclusion of this component helps the modelling of mean temperatures, it is not yet clear what climatic mechanisms are forcing this growth response (Wilson and Luckman, 2002).

Comparison between the two reconstructions

The independently derived REG and IBC reconstructions correlate well with each other (r = 0.92) and the instrumental record over their common periods (Figure 4) despite their relatively high regression standard errors (0.70, Table 3). The reconstructions show increasing temperatures from the mid-nineteenth century to *c.* 1940 with no clear trend over the last 60 years (Figure 4). The interannual and decadal fluctuations in both reconstructions show a remarkable similarity which indicates that the parsimonious IBC reconstruction provides comparable results to the more extensively sampled REG reconstruction. The IBC reconstruction is therefore considered to be a regionally representative proxy for maximum May–August temperatures prior to 1845.

The reconstructed maximum summer-temperature record, 1600–1997

The IBC reconstruction (Figure 5) indicates that May–August maximum temperatures are 0.28°C (1600–1997) and 0.38°C (1600–1900) below the 1961–1990 mean. 1641 (–2.94°C) and 1958 (+1.44°C) are reconstructed as the most extreme years. The reconstruction indicates two prolonged cooler, though variable, periods, *c.* 1620–1710 and 1775–1880, separated by warmer conditions that approached late twentieth-century normals in the early eighteenth century (Figure 5). Decadal means for the 1710s and the 1720s are 0.05° and –0.03°C, respectively, and the 1790s and 1750s also rank among the 10 warmest decades. Nevertheless, the twentieth century is clearly the warmest period, including 9 of the 10 warmest years and 6 of the 10 warmest decades (Table 4). The coldest years are more widely distributed throughout the record (note, however, 1876, 1880, 1881 and 1899, Table 4) and the coldest decades are divided equally between the seventeenth (1620s–1640s, 1660s, 1690s) and the late eighteenth and nineteenth centuries (1780s, 1800–30s, 1870s–80s). This general pattern is similar to other regional and Northern Hemisphere reconstructions (see below). On average, however, the seventeenth century is marginally colder than the nineteenth century (–0.53: –0.49°C). Both the IBC and REG reconstructions model the rise in maximum temperatures from the 1880s to 1940s that is seen in the instrumental climate record.

Discussion

Selection of appropriate climate measures

Based on our review of the literature, only Earle *et al.* (1994) have previously reconstructed maximum monthly temperatures from tree-ring records. This is surprising given that a relationship between maximum summer temperatures and tree growth appears quite plausible in temperature-limited environments. The superior 'fit' of maximum compared with mean temperatures in our regression calibrations may be linked to recent temperature changes. Examination of the instrumental record (Figure 6) indicates that the pattern and absolute magnitude of variation in maximum, mean and minimum temperatures are very similar for the first two-thirds of the twentieth century but there has been a marked reduction in the maximum–minimum range since the 1970s. Moreover, minimum temperatures exhibit a much greater relative increase than maximum temperatures. The poorer performance of calibration trials using mean-temperature data (Table 3) is most marked in the underprediction of warmer years in the recent instrumental record and overprediction of the cooler years in the late nineteenth century. As mean temperatures are determined by averaging maximum and minimum values, these calibration problems may reflect the increased influence of rising minimum temperatures on the mean-temperature record.

Recent studies of Canadian (Skinner and Gullett, 1993; Vincent *et al.*, 1999), mountain (Barry and Seimon, 2000) and global (Karl *et al.*, 1993; Easterling *et al.*, 1997; Dai *et al.*, 1999) temperature records indicate that during the twentieth century minimum temperatures were rising much more rapidly than maximum temperatures. It is therefore possible that the observed changes in temperature relationships in British Columbia are reflecting this global phenomenon. However, the dramatic change in these temperature relationships in Interior British Columbia (Figure 6)

Table 3 Calibration and verification statistics for climate reconstructions

Maximum May–August temperatures

	Calibration							Verification											
	Period	r	r^2	aR^2	SE	N	n	Period 1	r	RE	CE	PM	ST	Period 2	r	RE	CE	PM	ST
REG	1912–1953	0.80	0.65	0.63	0.49	6	2	1895–1911	0.77	0.28	0.04	2.41	13/2	1954–1995	0.72	0.44	0.44	2.92	31/9
	1954–1995	0.72	0.52	0.49	0.86	6	2	1895–1911	0.77	0.68	0.51	2.58	12/3	1912–1953	0.79	0.59	0.58	3.47	31/9
	1912–1995	0.74	0.55	0.53	0.70	6	2	1895–1911	0.77	0.62	0.45	2.48	13/2						
	Full model DW = 1.65																		
	Period	r	r^2	aR^2	SE	N	n	Period 1	r	RE	CE	PM	Sign	Period 2	r	RE	CE	PM	Sign
IBC	1912–1951	0.79	0.62	0.60	0.52	4	2	1895–1911	0.85	0.41	0.20	2.12	13/2	1952–1991	0.72	0.44	0.44	2.82	33/7
	1952–1991	0.73	0.53	0.50	0.84	4	2	1895–1911	0.84	0.55	0.37	1.95	13/2	1912–1951	0.76	0.55	0.55	3.35	33/7
	1912–1991	0.74	0.54	0.53	0.70	4	2	1895–1911	0.84	0.58	0.42	2.06	13/2						
	Full model DW = 1.62																		

Mean May–August temperatures

	Calibration							Verification											
	Period	r	r^2	aR^2	SE	N	n	Period 1	r	RE	CE	PM	ST	Period 2	r	RE	CE	PM	ST
REG_m	1912–1953	0.69	0.48	0.44	0.44	6	3	1895–1911	0.64	0.43	0.21	2.09	12/3	1954–1995	0.73	0.60	0.52	3.70	32/8
	1954–1995	0.74	0.55	0.52	0.61	6	3	1895–1911	0.63	0.70	0.24	3.83	13/2	1912–1953	0.67	0.39	0.13	4.28	33/7
	1912–1995	0.74	0.55	0.53	0.52	6	3	1895–1911	0.64	0.62	0.30	2.41	13/2						
	Full model DW = 1.55#																		
	Period	r	r^2	aR^2	SE	N	n	Period 1	r	RE	CE	PM	Sign	Period 2	r	RE	CE	PM	Sign
IBC_m	1912–1951	0.67	0.45	0.42	0.45	4	2	1895–1911	0.71	0.39	0.13	1.95	11/4	1952–1991	0.69	0.37	0.31	3.23	31/9
	1952–1991	0.69	0.48	0.45	0.64	4	2	1895–1911	0.71	0.34	–0.40	1.74	10/5	1912–1951	0.67	0.30	0.17	3.09	26/14
	1912–1991	0.66	0.44	0.42	0.57	4	2	1895–1911	0.71	0.42	–0.02	1.75	11/4						
	Full model DW = 1.35#																		

r = correlation coefficient; r^2 = explained variance; aR^2 = square of the multiple correlation coefficient following adjustment for loss of degrees of freedom; SE = Standard error of the estimate. N = number of possible predictors; n = number of predictors entered into regression; RE = Reduction of error statistic; CE = coefficient of efficiency statistic; PM = Product means test (Fritts, 1991); ST = Sign test (Fritts, 1976), showing ratio of agrees/disagrees. All r, r^2, aR^2, PM and Sign values are significant at the 95% confidence level except those that are highlighted by grey boxes. RE and CE values greater than zero indicate good model skill. #denotes that the DW test identified significant autocorrelation in the residuals at 99%.

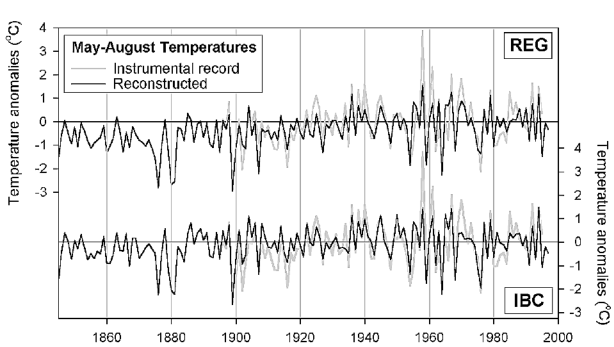

Figure 4 Comparison of the IBC and REG reconstructions of maximum May–August temperatures with each other and with the instrumental climate record.

coincides with the 1976 North Pacific Climate shift in the PDO (Ebbesmeyer *et al.*, 1991; Mantua *et al.*, 1997) which could provide an additional, more proximal, cause. Paradoxically, none of the temperature series show a similar response to the PDO shifts that occurred in 1925 and 1946. Further investigations are needed to determine the possible cause and spatial extent of the changing temperature relationships observed in these records which are real and have important implications for dendroclimate studies.

Other recent dendroclimate studies using maximum density (Briffa *et al.*, 1998a; 1998b) and ring-width data (Jacoby and D'Arrigo, 1995) have shown divergence in the decadally smoothed trends of growth and mean temperatures over recent decades. Several explanations have been suggested for these changing relationships (e.g., Jacoby and D'Arrigo, 1995; Vaganov *et al.*, 1999) involving changes in the sensitivity of these trees to the limiting factors that control growth. Our results suggest that these changing relationships may, in part, reflect changes in the climate record itself. Tree growth in these temperature-limited

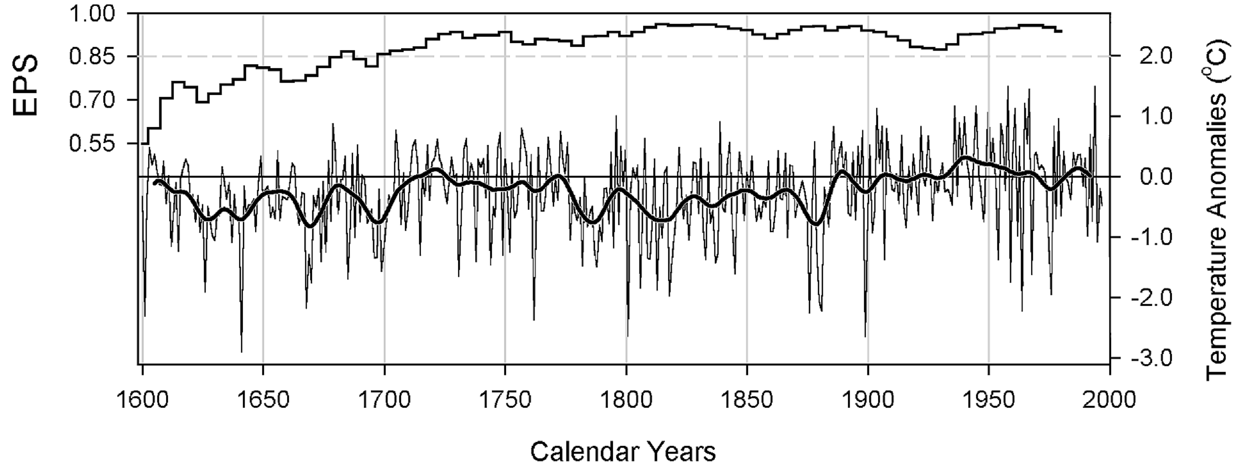

Figure 5 Time-series plot of the IBC reconstruction, 1600–1997. Temperature anomaly reference period = 1961–1990. The black smoothed line is a 20-year cubic smoothing spline. The EPS values are plotted for 30-year periods lagged by five years. The EPS values are a weighted mean of the EPS values of the original MXD and RW predictor series. The regression beta weights were used as the weighting term.

Table 4 Summary characteristics of the IBC maximum May–August temperature reconstruction: anomalies are calculated with respect to the 1961–1990 mean (anomalies based on the 1901–1980 instrumental means would be 0.07°C warmer)

10 Most extreme years				10 Warmest and coldest decades				Long-term means	
Year	Coldest	Year	Warmest	Year	Coldest	Year	Warmest	Years	Value
1641	–2.94	1958	1.44	1781	–0.88	1931	0.14	1601–1700	–0.53
1899	–2.70	1967	1.39	1811	–0.85	1941	0.12	1701–1800	–0.25
1801	–2.69	1965	1.15	1621	–0.83	1721	0.05	1801–1900	–0.49
1762	–2.41	1950	1.14	1691	–0.81	1951	0.03	1901–1997	–0.02
1601	–2.38	1938	1.12	1801	–0.74	1961	0.03		
1876	–2.30	1945	1.11	1871	–0.74	1901	0.02		
1881	–2.27	1904	1.08	1661	–0.73	1711	–0.03	1600–1997	–0.28
1964	–2.26	1961	1.07	1641	–0.65	1921	–0.06	1600–1900	–0.38
1668	–2.22	1796	0.95	1831	–0.56	1791	–0.13		
1880	–2.10	1940	0.93	1631	–0.50	1751	–0.17		

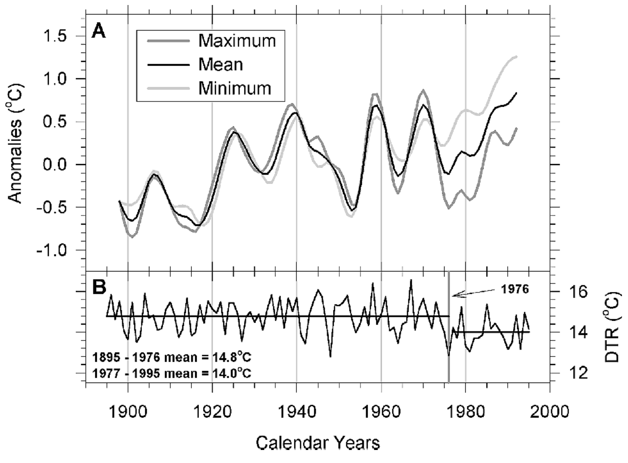

Figure 6 (A) Plots of maximum, mean and minimum May–August temperature anomalies (reference period = 1901–1980) for the BC regional series developed in this paper. (B) May–August diurnal temperature range.

environments may be more strongly influenced by summer daytime maximum temperatures than night-time minimum values. Therefore, growth trends may more closely reflect changes in maximum rather than mean or minimum temperatures. Considerable experimental work and further studies are necessary to validate this suggestion, but our results (and caution) suggest that calibration should be carried out against a range of temperature variables rather than simply using the mean, as has been conventionally done in the past. (See Wilson and Luckman, 2002, for more discussion on this issue.)

Comparison with other proxy reconstructions

Several summer-temperature reconstructions have recently been developed for western North America (Table 5). These records all utilize spruce (either *P. engelmannii* or *P. glauca*), are adjacent to or include Interior British Columbia and use different combinations of RW and MXD data. The Banff/Jasper (BJR, St George and Luckman, 2001) and British Columbia/Pacific North West (BCPNW1, Briffa *et al.*, 1992) reconstructions both utilize large networks of sites and exclusively RW (BJR) or MXD (BCPNW1) data. The BJR reconstruction is based on 14 treeline sites between *c.* 53° 20′N, 120° 40′W and 50° 36N and 115° W in the Canadian Rockies. The BCPNW1 (Briffa *et al.*, 1992) reconstruction is based on 23 chronologies from the Schweingruber network (Schweingruber, 1988), including sites from the cordillera in Washington, British Columbia and Alberta between 42° 30′–57° 30′N and 115–135° W. The Athabasca reconstruction (ATHA, Luckman *et al.*, 1997) utilizes RW and MXD chronologies from a single site close to the Columbia Icefield at *c.* 52° 15′N, 117° 15′W, approximately 300 km NNE of the Park Mountain site (Figure 1). (The Athabasca MXD and RW chronologies are composites from several collection areas immediately adjacent to each other. Some of these RW data are input into separate chronologies in the BJR data set. There are no common data between the

BCPNW1 and ATHA or IBC chronology data sets.) These reconstructions all involve a 4–6 month 'summer' season that includes June, July and August (Table 5). The Mann *et al.* (1999) reconstruction of Northern Hemisphere mean annual temperatures is shown for comparative purposes and was developed using a variety of high-resolution proxy climatic variables (Table 5).

Although these reconstructions are for different geographic regions and the seasonal temperature parameter reconstructed varies, examination of Figure 7 clearly suggests that some of the differences between these reconstructions are related to the tree-ring data used to develop them. The three reconstructions using both RW and MXD data are much more similar than those using either parameter separately. The BJR reconstruction, using RW alone, is the most distinctive with a strong low-frequency signal and different timing for the coldest and warmest periods during the nineteenth century. This strong low-frequency component is seen in other spruce temperature reconstructions for North America (e.g., D'Arrigo and Jacoby, 1992) and the general pattern is not dissimilar to the dominant ring-width signal in the BC chronologies presented here (PC2, Figure 3). However, this reconstruction is not significantly correlated with the other reconstructions prior to 1840 (Table 6).

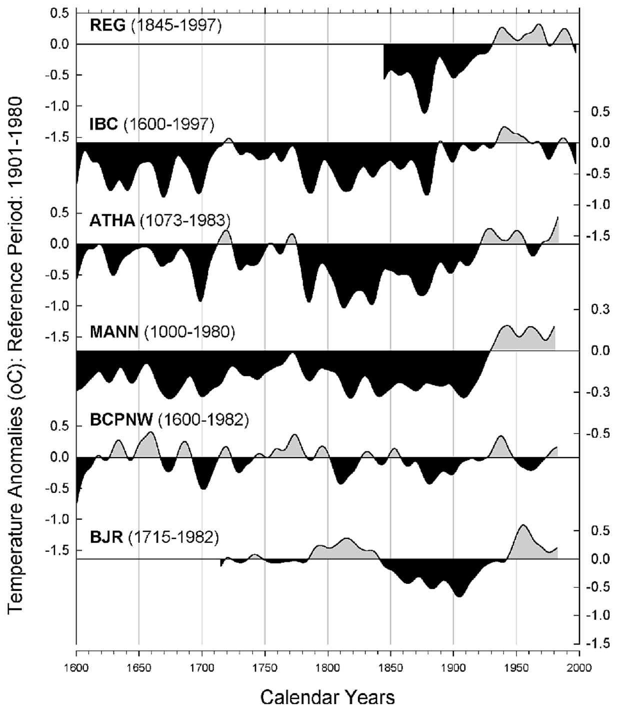

Figure 7 Low-pass filtered time series (20-year cubic smoothing spline) of the five summer temperature reconstructions derived from *picea* in the southern Canadian Cordillera. The reconstructed temperature anomalies shown are May–August maximum temperatures (REG, IBC); April–August mean temperatures (ATHA); April–September mean temperatures (BCPNW); June–September mean temperatures (BJR) and mean annual Northern Hemisphere (MANN; see text and Table 5). The IBC, REG, ATHA and BJR reconstructions were originally developed as anomalies from a 1961–1990 base period. However the average (maximum-mean) range of the BC regional temperature record for 1961–1990 is 0.22°C lower than that for the 1901–1980 period (see Figure 6). Therefore comparison of the maximum and mean temperature series based on 1961–1990 normals would show a relatively greater temperature depression in the mean anomaly series in the first two-thirds of this series. A similar effect occurs when the IBC maximum temperature reconstruction is plotted against the ATHA mean-temperature reconstruction using 1961–1990 'normals': the nineteenth century temperature anomalies in the Athabasca record become much colder relative to the IBC record. Recalculating the REG, IBC, ATHA and BJR series based on 1901–1980 'normals' (as is done also in Figure 6) makes the absolute values of these anomalies more directly comparable by removing effects related to the recent changing relationships between mean and maximum temperatures.

The BCPNW1 reconstruction of Briffa *et al.* (1992) utilized MXD chronologies standardized by smoothing splines with a frequency-response cut-off set at two-thirds the length of each series. Although this reconstruction correlates reasonably well with the IBC, ATHA and REG reconstructions at the interannual and decadal scales (Table 6), it shows little centennial-scale variability (Figure 7). The correlation of the 'smoothed' BCPNW1 and IBC reconstructions is particularly poor in the seventeenth century (Table 6D). The lack of centennial-scale variability probably results from the combined effect of the flexible standardization process used and the sole reliance on MXD data. An alternate 'IBC_{mxd}' reconstruction, utilizing only MXD predictors, calibrated 40% of the maximum May–August temperature variance. Strong linear trends in the residual series indicated that utilizing MXD data alone inadequately modelled lower-frequency variability (analysis not shown).

The ATHA reconstruction (Luckman *et al.*, 1997) utilizes both RW and MXD data and is most directly comparable to the IBC and REG reconstructions. It has the highest correlations with the annual and smoothed versions of both reconstructions (Table 6) and strong covariance between the ATHA and IBC reconstructions is clearly seen in Figure 7. The strong common decadal variance between the ATHA and IBC reconstructions is also demonstrated by correlations >0.79 between the filtered series prior to the present century (Table 6D). The similarity of these two reconstructions in the seventeenth century is particularly encouraging: the Athabasca chronology is strongly replicated in this interval and confirms the signal in the weakest part of the IBC reconstruction (Figure 5). The poorest correlations between these reconstructions are in the twentieth century ($r = 0.55$, 1895–1982, Table 6D). Close inspection of the REG, IBC and ATHA series in Figure 7 shows that both BC reconstructions peak in the 1940s whereas ATHA peaks in the 1930s and 1950s. These differences between the two regions are surprising given the concordant variation of decadal trends prior to the twentieth century and the correlation between the two temperature records ($r = 0.87$ for similarly filtered series, 1895–1977). A reassessment of the ATHA reconstruction is currently in progress to address these issues.

It seems clear that most of the interannual and decadal variability in these reconstructions is derived from the MXD data but the low frequency is based largely on the RW series (or its absence, in the BCPNW1 case). At longer timescales, both the IBC and ATHA reconstructions (Figure 7) indicate that temperatures during the nineteenth century were about half a degree cooler than mean twentieth-century values with slightly more severe conditions at the Athabasca site, particularly in the early 1800s (Figure 7). The IBC reconstruction indicates that mean maximum temperatures in the seventeenth century were similar to the nineteenth-century values. Temperatures at the Athabasca site, though cool, appear to have been relatively warmer than Interior British Columbia during this time. Both reconstructions suggest the early eighteenth century was comparable to average twentieth-century conditions.

The ATHA reconstruction is derived from chronologies within an area of a few square kilometres. Justification of the regional representativeness of this record was based on comparison with other proxy climate data, notably the local and regional record of glacier fluctuations in the Rockies (Luckman *et al.*, 1997; Luckman, 2000). As the reconstruction was essentially developed from a single site, it was impossible to determine directly whether that record was unduly influenced by local climatic conditions related to the proximity of the Columbia Icefield. The IBC reconstruction is derived from tree-ring data at sites considerable distances from glaciers. The similarities between the IBC and ATHA reconstructions now provide clear, mutual, verification of the broad pattern

Table 5 Temperature reconstructions derived from *picea* chronologies in the southern Canadian Cordillera

Code	Reference	Region	Species	Seasonalized reconstruction	Measured ring parameters	R^2_{adj}	Length
REG	This study	British Columbia	Engelmann spruce	MAX May–August	RW + MXD	0.53	1845–1997
IBC	This study	British Columbia	Engelmann spruce	MAX May–August	RW + MXD	0.53	1600–1997
BJR	St George and Luckman (2001)	Rocky Mountains	Engelmann spruce	MEAN June–September	RW	0.35	1715–1982
ATHA	Luckman *et al.* (1997)	Columbia Icefield	Engelmann spruce	MEAN April–August	RW + MXD	0.39	1073–1983
BCPNW1[#]	Briffa *et al.* (1992)	British Columbia/Pacific Northwest	Several	MEAN April–September	MXD	R	1600–1982
MANN	Mann *et al.* (1999)	Northern Hemisphere	N/A	Annual	N/A	*c.* 0.37	1000–1980

[#] = The longer of the two Briffa *et al.* (1992) reconstructions is used here for comparison. R = regional average, with only the component correlations given (Briffa *et al.*, 1992). N/A = The Mann *et al.* reconstruction uses a mix of tree-ring and other proxy climate data.

Table 6 Correlations between the two BC temperature reconstructions and other proxy records of past temperature (for details, see Table 5)

Annual series

(A) REG reconstruction

Period	IBC	ATHA	BJR	BCPNW1	MANN
1895–1982	0.92	0.67	0.45	0.60	0.31
1845–1982	0.92	0.66	0.44	0.58	0.39

(B) IBC reconstruction

Period	REG	ATHA	BJR	BCPNW1	MANN
1895–1982	0.92	0.63	0.35	0.53	0.13*
1845–1982	0.92	0.61	0.37	0.52	0.24
1715–1844	–	0.68	0.12*	0.57	0.22
1600–1714	–	0.60	–	0.43	0.22

Low-pass filtered series**

(C) REG reconstruction

Period	IBC	ATHA	BJR	BCPNW1	MANN
1895–1977	0.66	0.66	0.84	0.42	0.84
1850–1977	0.88	0.87	0.75	0.50	0.94

(D) IBC reconstruction

Period	REG	ATHA	BJR	BCPNW1	MANN
1895–1977	0.66	0.55	0.50	0.51	0.66
1850–1977	0.88	0.82	0.54	0.50	0.64
1720–1844	–	0.88	–0.66	0.49	0.60
1605–1714	–	0.65	–	0.14	0.16

IBC and REG = this paper: ATHA = Luckman *et al.* (1997); BJR = St George and Luckman (2001); BCPNW1 = Briffa *et al.* (1992); MANN = Mann *et al.* (1999).
* = not significant at 95% confidence limit.
**The low-pass filtered series were calculated with a 20-year cubic smoothing spline. Where necessary, five years were truncated from the end of the series to remove potential end effects. Standard methods for quantifying significance limits are not appropriate for these low-pass filtered series (Fritts, 1976: 324). The correlations merely provide a guide to the common low-frequency variability between two series.

and amplitude of the temperature fluctuations across SW Alberta and adjacent southern BC since 1600. More particularly, they indicate that the severe conditions at the end of the seventeenth century that were associated with significant tree mortality at the Athabasca site (Luckman and Kavanagh, 1998; Kavanagh, 2000) were regional in extent.

The IBC and ATHA reconstructions present a coherent general picture of conditions over the last 400 years. Severe conditions in the seventeenth and nineteenth centuries are separated by generally milder conditions for most of the eighteenth century. Moreover, the coincidence of these temperature reconstructions with the historical record of glacier maxima since 1600 (Luckman, 2000) clearly indicates a strong summer temperature control on regional glacier fluctuations. There are strong similarities between both the IBC and ATHA reconstructions and the Mann *et al.* (1999) reconstruction (Figure 7), particularly at the decadal and lower-frequency scales (Table 6D). These results suggest that the low-frequency temperature trends in the southern Canadian Cordillera are strongly related to large-scale global trends over the last 400 years.

Conclusion

This paper reports results from an area in southern British Columbia that previously lacked high-resolution palaeotemperature records. Two independent maximum temperature reconstructions have been developed that both reconstruct 53% of the variance in the regional instrumental climate record and correlate at $r = 0.92$ over their common interval. The shorter REG reconstruction (1845–1997), using 12 RW and 5 MXD chronologies, verifies the regional signal in the longer (1600–1997) IBC reconstruction, based on the three longest RW and two MXD chronologies held back from the REG analysis. These maximum temperature reconstructions calibrate considerably more of the climatic variance than previous mean-temperature reconstructions for this region (Table 5). The IBC reconstruction is very similar to the Athabasca reconstruction of Luckman *et al.* (1997) and these two records mutually verify their common proxy temperature records, confirming that both are regionally representative.

These new reconstructions are the first to generate proxy maximum temperature series in North America. They demonstrate that calibration models that verify >50% of the regional temperature variance can be obtained for this region using both RW and MXD data from *picea*. The stronger temperature signal in MXD data contributes mainly to the high-frequency signal whereas the ring-width data possess a more complex climate-related signal and provide information on low-frequency climatic variability.

Our results also indicate there have been recent changes in the relationships between mean, maximum and minimum temperatures in the instrumental climate record of this region that may compromise the utility of climate reconstructions based on mean-temperature data. Future reconstruction studies should calibrate on a variety of temperature measures rather than exploring only mean-temperature data. Further analyses of instrumental climate records and tree-ring growth/temperature relationships at treeline are needed to establish the generality of these findings. However, if the effects of these changing temperature relationships on the climate signal in tree-ring data are widespread, they have major implications for dendroclimatology that must be addressed in the ongoing discussion of late twentieth-century changes in tree-ring/climate relationships.

Acknowledgements

This work was supported by grants from the Natural Sciences and Engineering Research Council of Canada. We thank Gordon Jacoby and colleagues at the Tree-Ring Laboratory, Lamont Doherty Earth Observatory, for allowing access to and providing training on the Dendro 2003 system at Lamont. Margaret Colenutt and many individuals in the BC Parks Service, BC Ministry of Forests and Parks Canada gave us useful advice on potential sampling locations (and granted the necessary sampling permits). Climate data were provided courtesy of Walter Skinner of the Meteorological Service of Canada. This work has greatly benefited from discussions with Emma Watson and Don Youngblut at UWO and we thank Don for outstanding assistance in the field and laboratory. Figures 1 and 2 were prepared by Trish Chalk of the Cartographic Section, Geography Department, UWO. We thank Keith Briffa for his pithy editorial comments and suggestions.

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